Development of a novel empirical framework for interpreting geological carbon isotope excursions, with implications for the rate of carbon injection across the PETM

Supplementary Information

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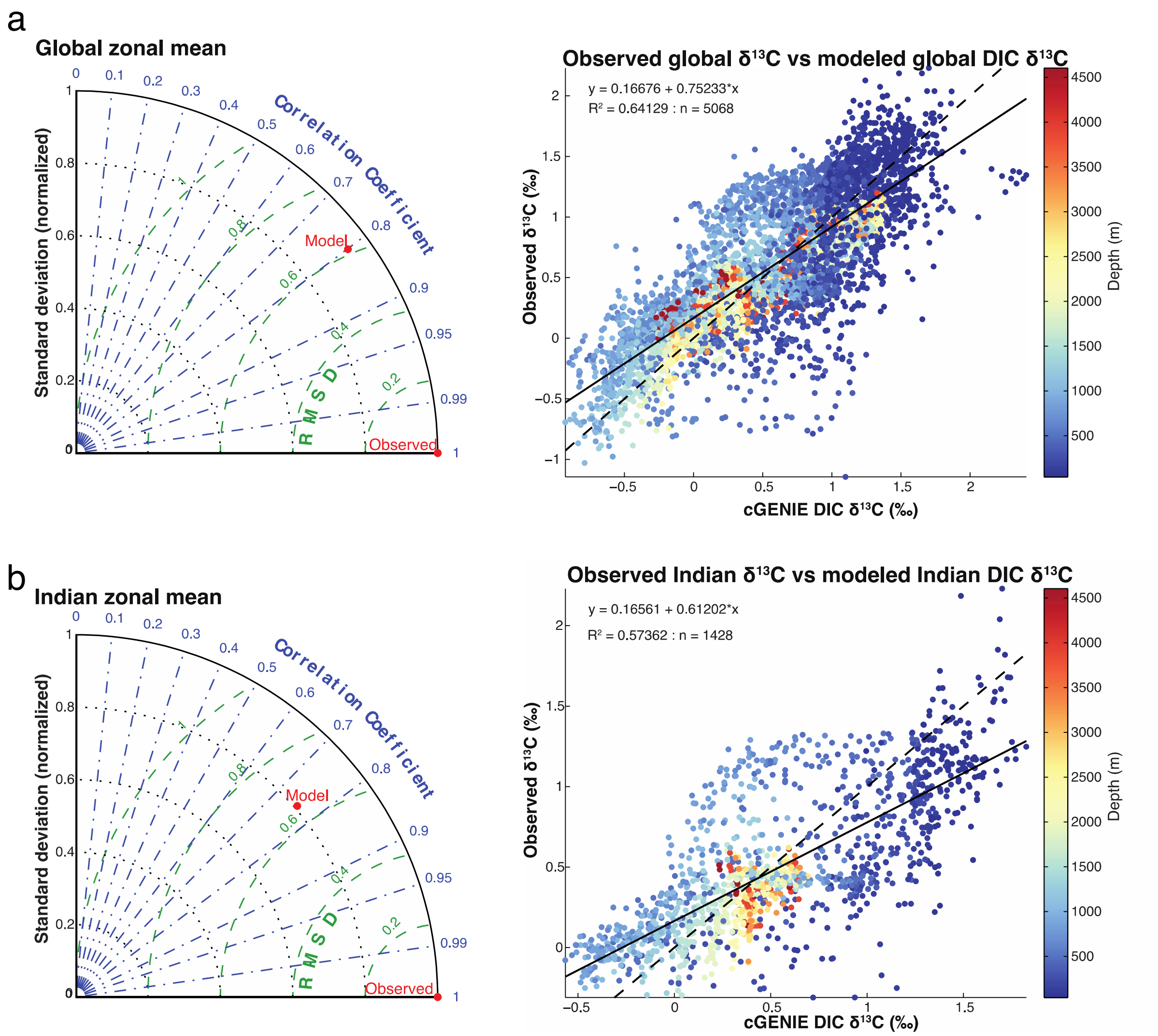


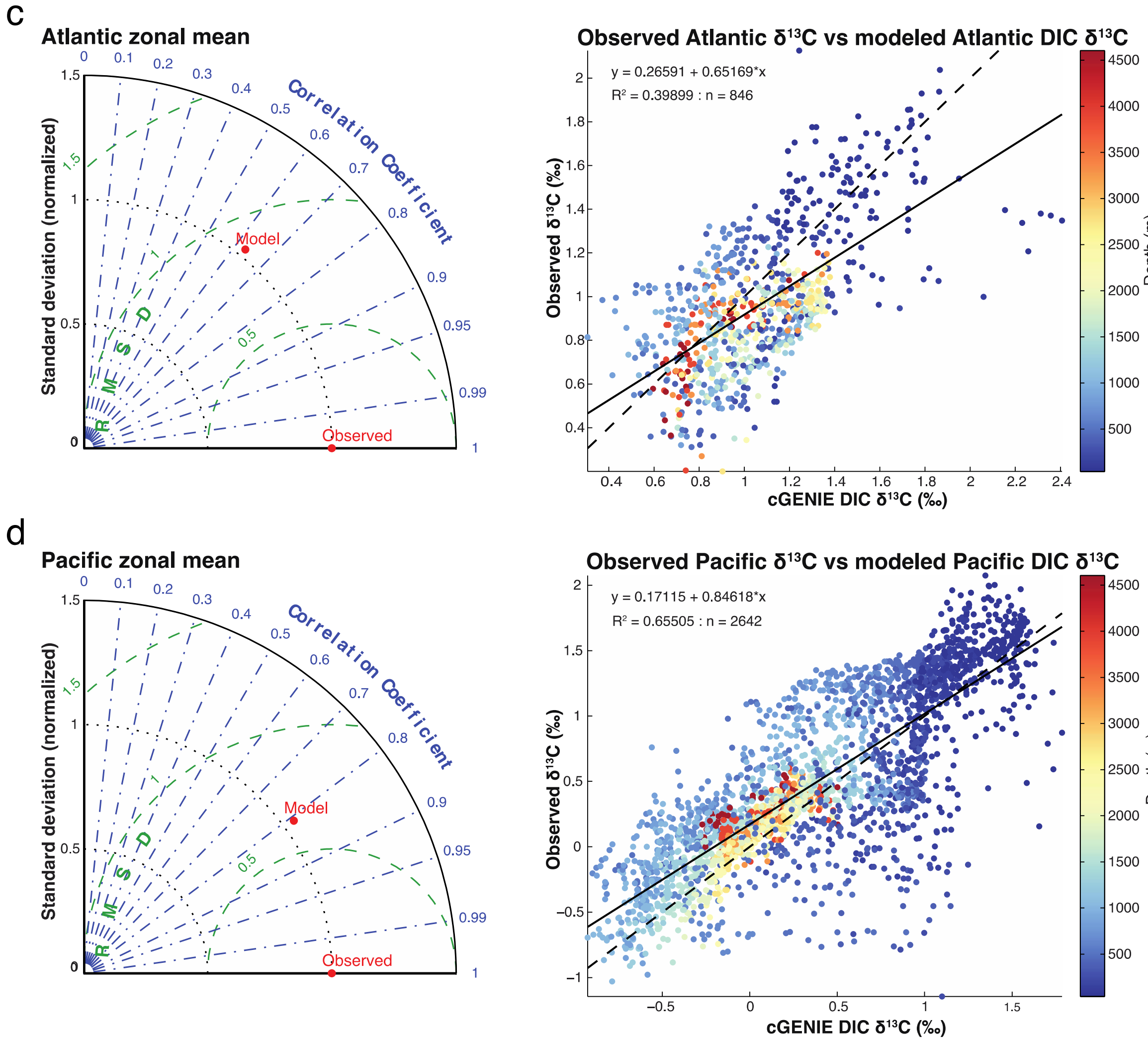


Figure S1. Statistical summary plots for model-data $\delta^{13}C$ evaluation including Taylor diagrams of observed versus modeled zonal mean (left column) and cross plots of observed versus modeled $\delta^{13}C$ with colors indicating ocean depth (right column) for a) global ocean, b) Indian ocean, c) Atlantic ocean, and d) Pacific ocean. Taylor diagrams summarize the relative skill of the model in reproducing the observed $\delta^{13}C$ pattern with similarity between model and observations quantified in terms of correlation (blue dashed lines), root mean square difference (RMSD; green dashed lines), and the amplitude of respective variations (reported as a normalized standard deviation; black dotted lines). For cross plots, solid black line indicates linear line of best fit, and dashed black line has a slope equal to 1.

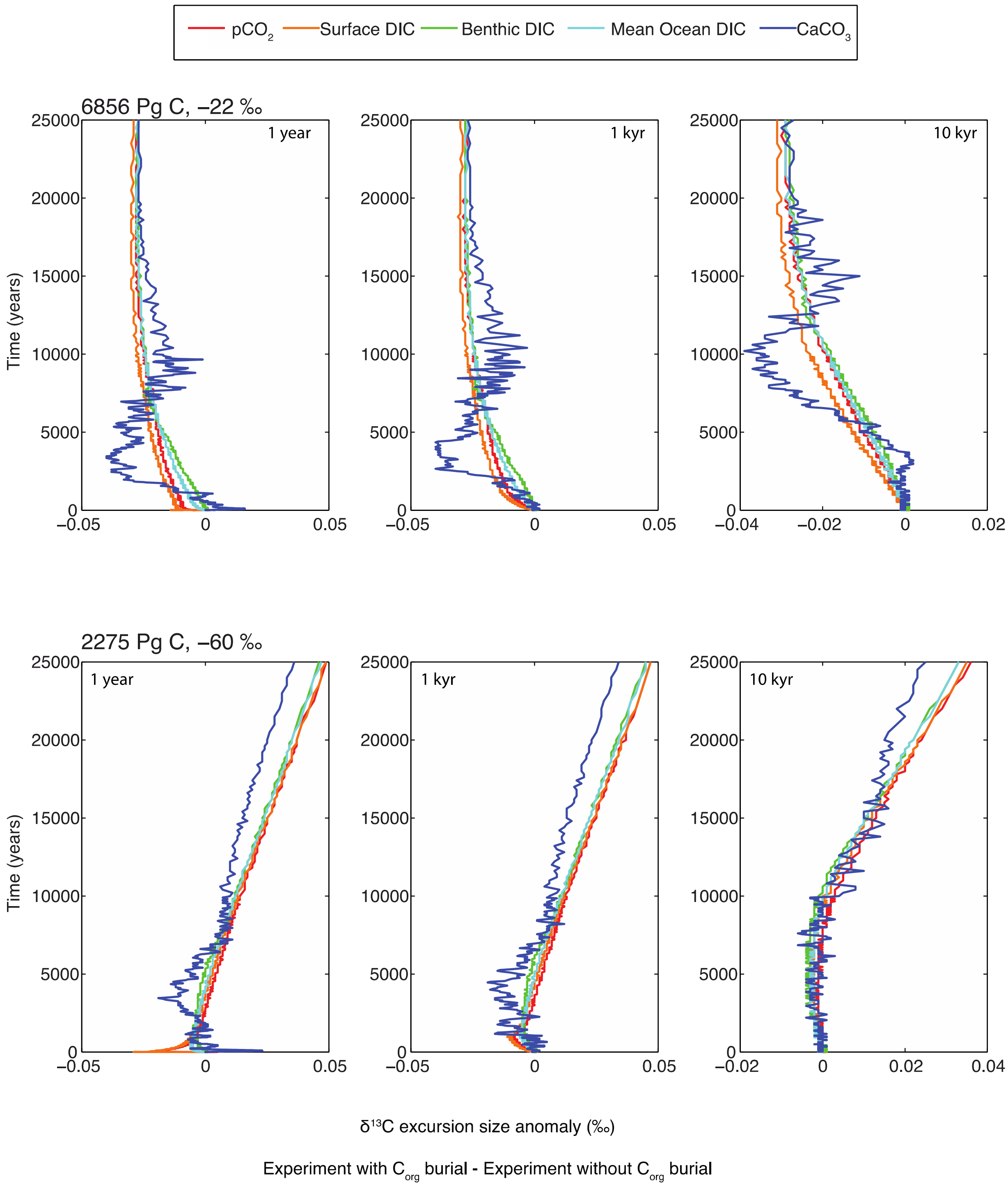
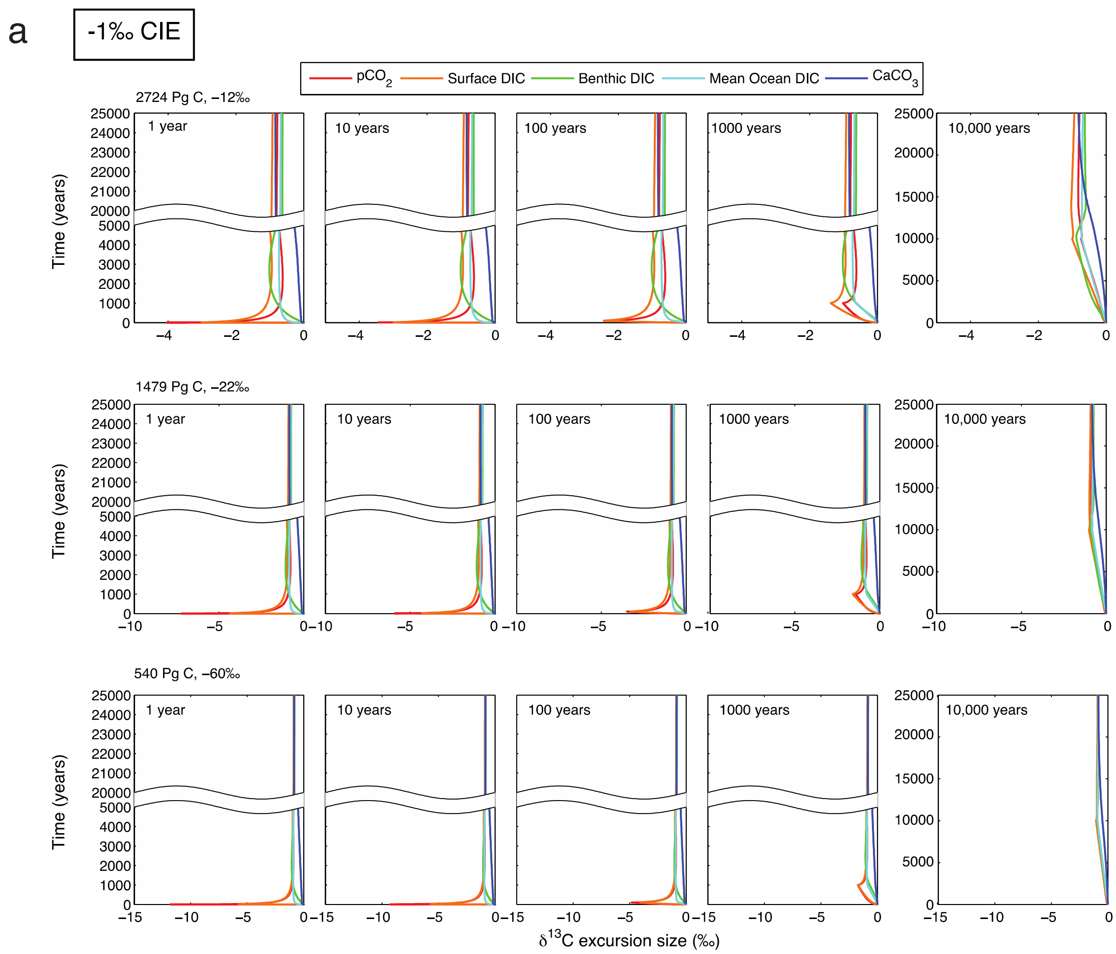


Figure S2. Test of the impact of revised spin-up methodology on experiment results. We implemented a new spin-up methodology to balance the global carbon cycle by burying organic carbon in shallow marine sediments as a function of area in the model shallow sediment grid (sites >175 m). The fractionation factor between carbonate and organic carbon was set at -30‰, carbonate burial was calculated the same as before, based on results from an initial closed system spin-up, and weathered $CaCO_3$ was set to the same $\delta^{13}C$ as buried $CaCO_3$. The volcanic carbon

$\delta^{13}C$ was set to -6‰, and we thus solved for the emissions flux of volcanic carbon and burial flux of organic carbon. The resulting spin-up differed from the previous spin-up without organic carbon burial by less than 1 ppm pCO_2 and less than 0.001‰ for the $\delta^{13}C$ of CO_2. However, to test whether using this revised isotopic mass balance would have any effect on the subsequent CO_2 release experiments, we also re-ran the six experiments plotted above, emitting either 6856 Pg C (-22‰) or 2275 Pg C (-60‰) over 1 yr, 1 kyr, or 10 kyr. Above, we show the difference in the $\delta^{13}C$ excursion size in each reservoir for each experiment using the previous methodology compared to the methodology including organic carbon burial. Excursion sizes differ by less than 0.05‰.



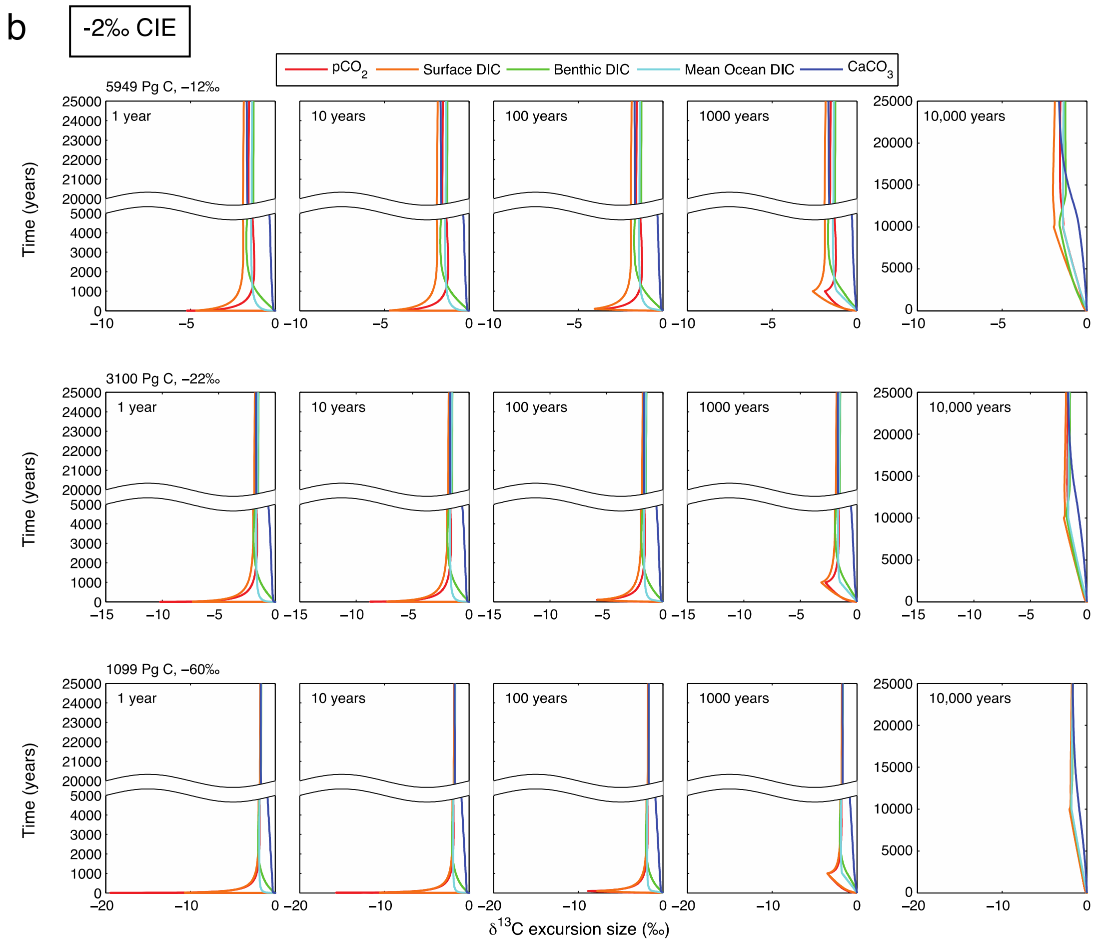


Figure S3. Results of carbon release experiments with masses selected to generate a -1‰ global CIE (a) and a -2 ‰ global CIE (b) with varying durations of carbon input. Top row) -12‰ carbon input, middle row) -22‰ carbon input and bottom row) -60‰ carbon input. Results are shown for experiments (from left to right) with duration of carbon input 1, 10, 100, 1000 and 10,000 years. Each line indicates the $\delta^{13}C$ with model time preserved in different modeled carbon reservoirs – atmospheric CO_2 in red, surface ocean dissolved inorganic carbon (DIC) in orange, benthic DIC in green, mean global ocean DIC in light blue, and sedimentary $CaCO_3$ in dark blue. All $\delta^{13}C$ excursions are adjusted relative to 0‰ in order to trace the relative size of the excursion instead of the absolute $\delta^{13}C$ values recorded in each reservoir. For carbon release durations of less than 10,000 years, the y-axis has a break from 5000 to 20,000 years.

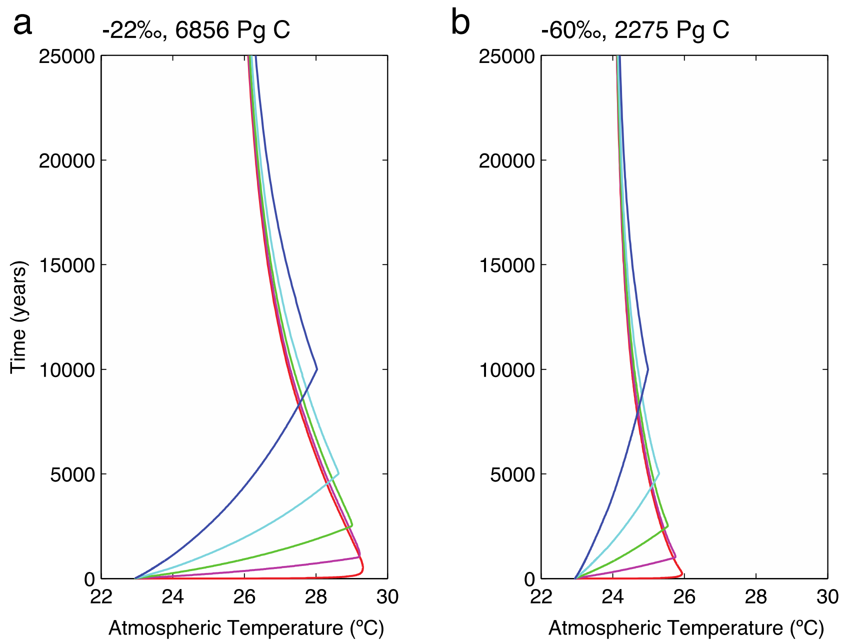


Figure S4. Change in atmospheric temperature (°C) for a) -22‰ carbon input of 6856 Pg C and b) -60‰ carbon input of 2275 Pg C for varying durations of carbon input. Red lines = 1 year release, pink lines = 1000 year release, green lines = 2500 year release, light blue lines = 5000 year release, and dark blue lines = 10,000 year release.

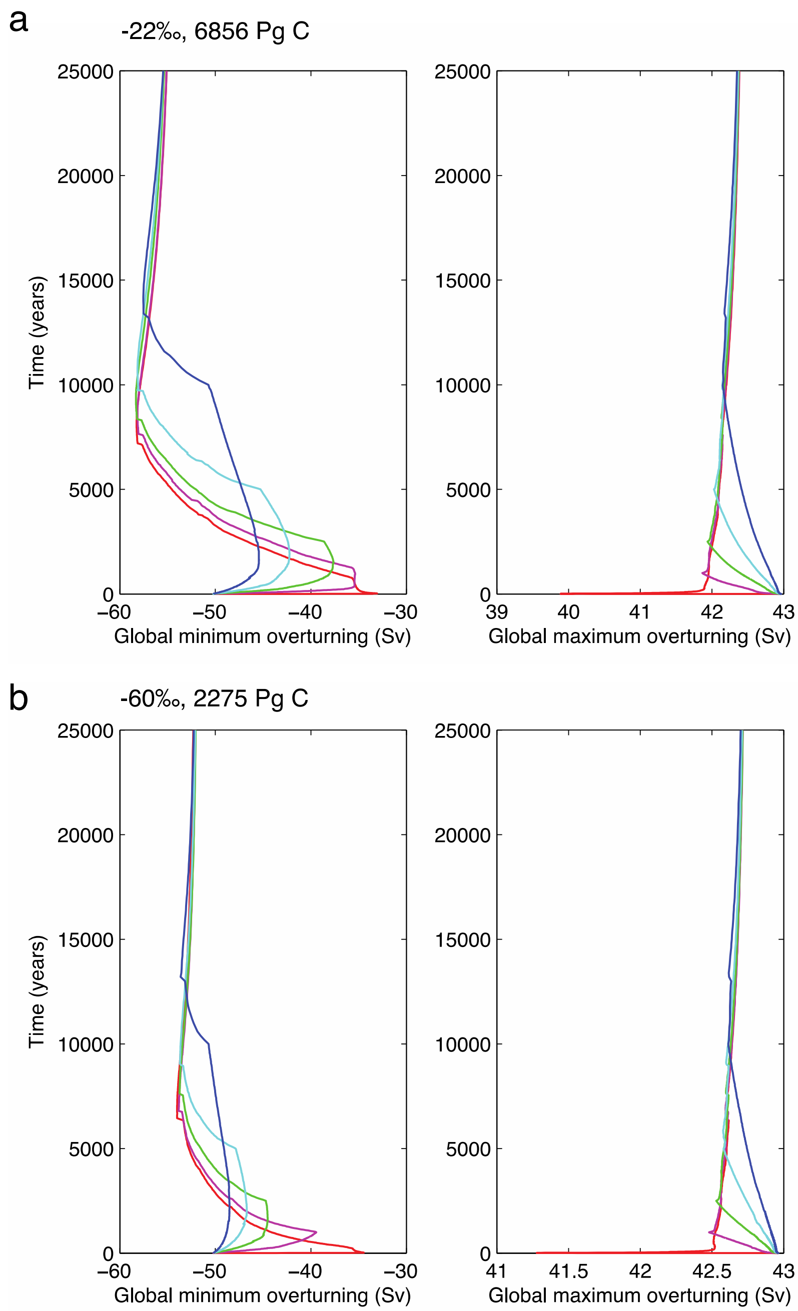


Figure S5. Change in meridional overturning streamfunction minimum (left) and maximum (right) for a) -22‰ carbon input of 6856 Pg C and b) -60‰ carbon input of 2275 Pg C for varying durations of carbon input. Red lines = 1 year release, pink lines = 1000 year release, green lines = 2500 year release, light blue lines = 5000 year release, and dark blue lines = 10,000 year release.

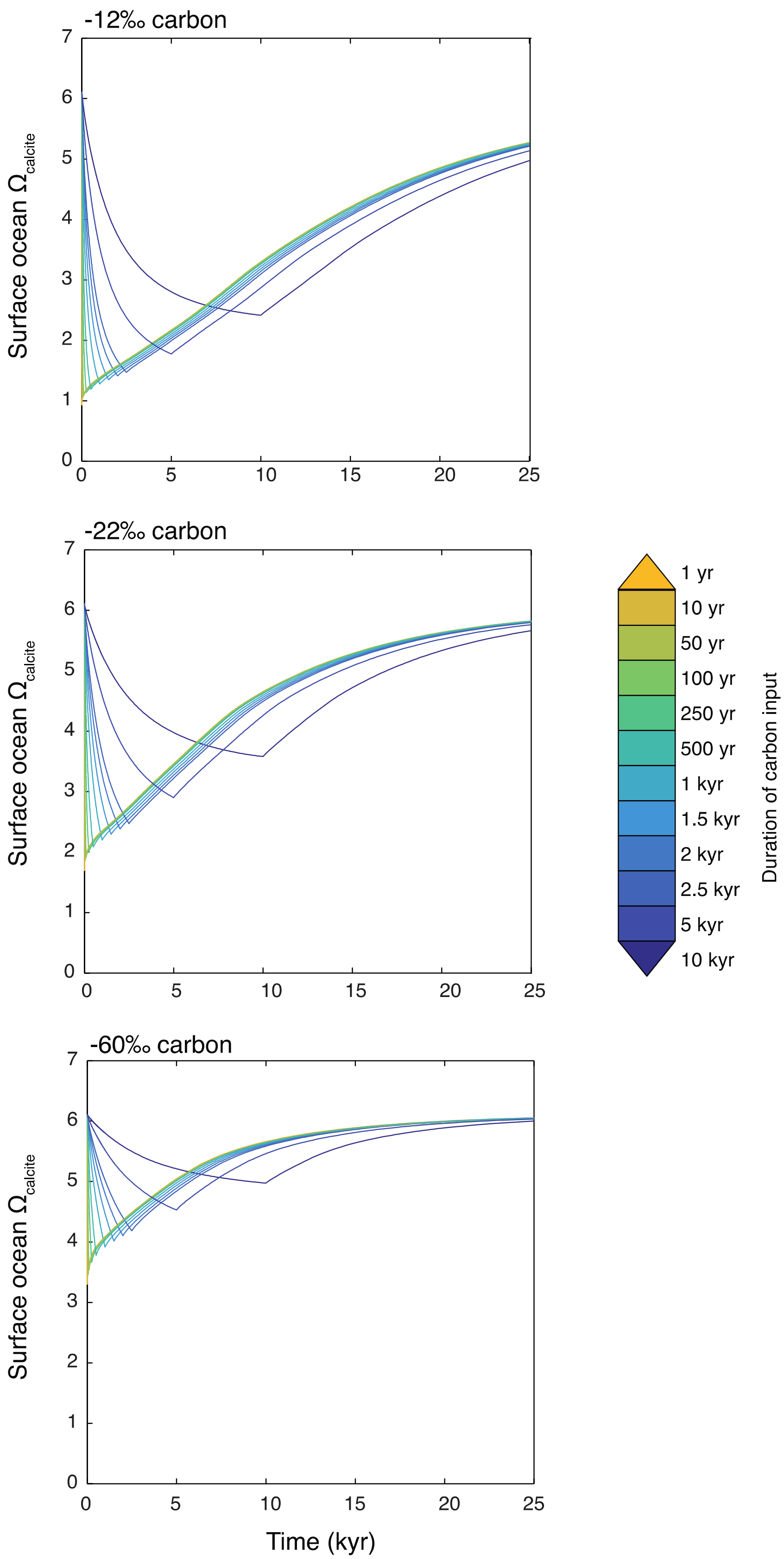

-12‰ carbon
-22‰ carbon
-60‰ carbon
Surface ocean Ω calcite
Time (kyr)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
1 yr
10 yr
50 yr
100 yr
250 yr
500 yr
1 kyr
1.5 kyr
2 kyr
2.5 kyr
5 kyr
10 kyr
Duration of carbon input

Figure S6. Change in mean ocean saturation state with respect to calcite ($\Omega_{calcite}$) for -12‰ input (top), -22‰ input (middle), and -60‰ input (bottom). Colored lines on each plot (see colorbar) indicate the duration of carbon release, from shortest (1 year, yellows) to longest (10 kyr, blues). Only the fastest release of the largest mass of carbon (14,578 Pg C for -12‰ case) causes the mean surface ocean to become undersaturated when emissions peak.

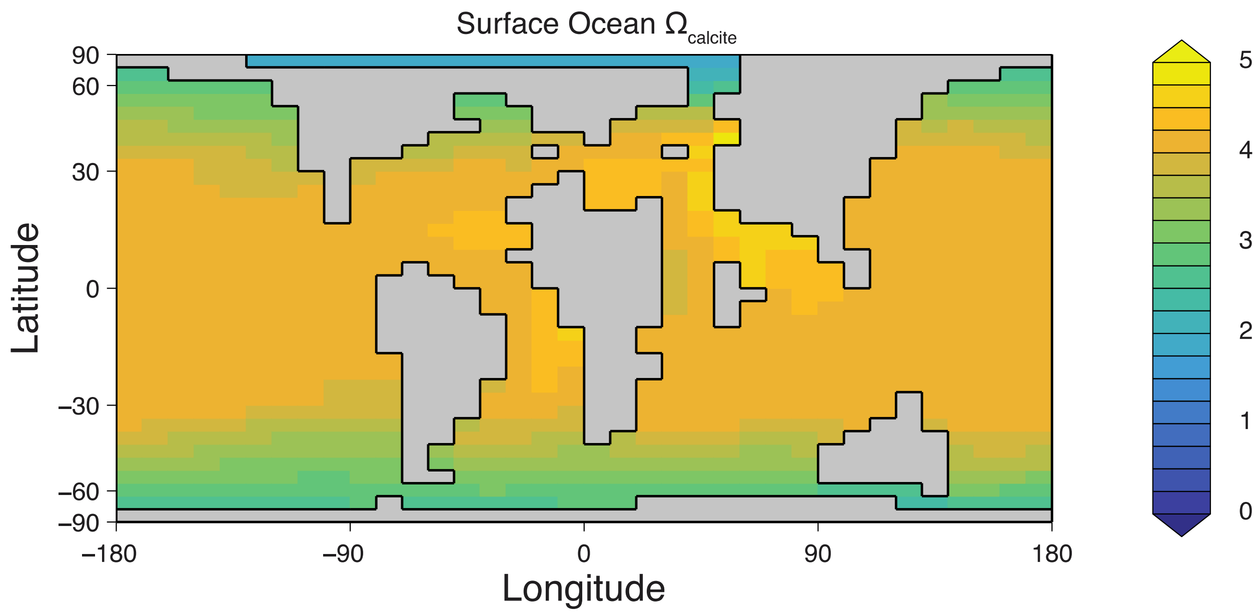


Figure S7. Surface ocean saturation state at year 2000 for the 2000-year release of 6856 Pg C (-22‰). No locations in the surface ocean become undersaturated. The drop in saturation state is most severe in the high latitude Arctic in cGENIE, which is dominated by freshwater input and is near $\Omega_{calcite}$=1 even before any carbon is added to the atmosphere.